An Analysis of Shaded Fuel Breaks on Fire Behavior

C-2 Boreal Spruce Upland and lowland black spruce, white and Engelmann spruce stands. Does not include spruce-sphagnum bogs. Photo shows upland black spruce.

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Executive Summary

Past disruptions of natural fire cycles, as well as other management practices, have resulted in wildfires of increasing intensity and severity. Treatment of hazardous fuel will help reduce the impacts of wildfires on communities and restore health to fire-adapted ecosystems. The National Fire Plan expands hazardous fuel treatment programs significantly, with greater focus on treatments intended to protect communities in the wildland urban interface. Fire management agencies are being directed to protect these communities and many fuel treatment projects are being implemented in the form of fuel reductions and fire breaks. These treatments are currently being evaluated to ensure that they are in fact giving these communities and sites the protection that is need.

Black spruce (*picea mariana*) is the problem fuel type in Alaska and poses the most threat to community protection. Black spruce is very susceptible to crown fires due to low crown base height with branches growing to and often into the ground. This leads to crown fire initiation from very low fire intensities. Crown fires in black spruce are usually passive, but active crown fires are common. Black Spruce stands are often many square miles in area and may abut village communities or major urban areas. Knowing these characteristics, fuel breaks involving pruning of ladder fuels and raising the crown base heights seems the logical choice.

This paper analyzed one such area against an area of control. The analysis revealed that on an average fire day the predicted fireline intensities of the treatment area was significantly different than the fireline intensities of the control area. Thus, the null hypothesis of treatment fireline intensity mean is equal to the control fireline intensity mean was rejected at $\propto = .05$, inferring that the treatment mean fireline intensity was not equal to the control mean fireline intensity. Analysis shows fireline intensities increased in the treated site.

Introduction

The Alaska Fire Service (AFS) is involved in constructing shaded fuel breaks at different locations around the state to provide communities and areas of high value with defensible space in the event of an approaching fire.

Based on studies done on crown fires at the Canadian Research Center in Fort Providence Northwest Territories, the Alaska Wildfire Coordination Group and the Joint Fire Sciences Committee have requested data and information be collected on the possible differences in the fire environment created by defensible space and fuel break projects.

This project: (a) provides a systematic study of the fuel moisture, temperature and wind speeds of the treated and untreated areas to determine the effects on the involved microclimates and (b) analysis historical weather data input into the BEHAVE program to predict the resulting fire behavior.

The Alaska Fire Service fire managers will review the results of this study.

Background Statement

The Bureau of Land Management in Alaska has instructed communities as well as being actively involved in the construction of shaded fuel breaks for several years. These fuel breaks are used in predominately Black Spruce (*Picea mariana*) stands, the problem fuel type in Alaska. While totally removing standing fuels in these identified areas would work to reduce fireline intensities, the aesthetics and livability of the affected areas and communities after treatment make this method undesirable.

The standard followed in the construction of shaded fuel breaks or treatments, consists of thinning trees to a 10 foot by 10 foot spacing, with the remaining trees limbed to a height of 4 feet. All cut trees and other woody debris are removed from the site or piled and burned after snow has covered the ground.

The baseline theory of a shaded fuel break is that if a crown fire burns to the break fireline intensities will be reduced due to crown bulk density reductions thus allowing for direct attack.

It has been proposed that this sort of fuel manipulation could result in dryer fine fuels due to increased surface winds and temperature, resulting in the undesired consequence of increased fire behavior and rate of spread. There have been minimal and inconclusive studies done on the effectiveness of this type of treatment. This project will analyze changes in predicted fire behavior in this type of fuel treatment.

Problem Statement

The Alaska fire community is uncertain that shaded fuel breaks constructed by thinning trees to a 10 foot by 10 foot spacing and pruning to a height of 4 feet will reduce fireline intensities enough to protect the communities identified as high risk.

Goals

Validate that shaded fuel breaks, as outlined in the National Fire Plan, are effective in black spruce stands.

Objectives

1. Analyze the gathered plot data to determine above ground biomass of the treatment and control areas.
2. Using accepted methods, determine the effects of the fuels treatment on fire behavior in comparison to the control area.
3. Determine if the fuels treatment has achieved a reduction in fire intensity compared to the control area.

Methods and Procedures

The Alaska Fire Service in coordination with the Joint Fire Sciences Committee and the Tanana Chiefs Conference had begun exploring shaded fuel breaks prior to this project. They have established 5 separate one acre plots on Fort Wainwright Alaska to study the species and time lag of regeneration. One plot remained untouched as the control plot. The four remaining plots had vegetation and trees removed to the specifications of 2 plots of 8 feet by 8 feet spacing of the leave trees and 2 plots of 10 feet by 10 feet spacing of the leave trees. One plot from each spacing group was pruned to the height of 4 feet with the other being not pruned at all.

Data gathering

Paired data was collected on the control plot (center of plot coordinates; 64 49.421 X 147 32.852) and the plot with trees spaced 10 feet apart and pruned to a height of 4 feet, here after referred to as the treatment plot (center of plot coordinates; 64 49.340 X 147 32.708). The distance between the centers of the two plots is approximately 633 feet. Temperature, humidity, precipitation and wind speed were collected using one HOBO™ weather station in each plot[1]. Precipitation was collected only in the treatment plot due to the close proximity of the control plot. The collected data was then used to calculate components of the Canadian Fire Weather Index System (Appendix C) to see if differences occurred between the two sites. The components calculated were the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and the Drought Code (DC).[2] The FFMC, DMC and DC roughly correspond to the 1 hr., 10 hr. and 100 hr. fuels respectively in the NFFDRS system. The results were input into the FBP 97 system to analyze fire weather outputs. This strategy proved to be non-workable because the FBP system is not sensitive enough to give reliable results for fuels manipulation.[3] The analyzed data was kept in this study as a supplement to show the calculated differences in the above fuel moisture codes. (Appendix C).

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[1] Mini RAWS purchased from Onset corp. Specifics in Appendix B
[2] Tables for the Canadian Forest Fire Weather Index System. 1987
[3] Per conversations with Martin E. Alexander.

Methods for analysis

The one sample t-test was used to compare the treatment to the control data. The following hypotheses were used for all testing:

Null hypothesis:

Treatment fireline intensity mean = Control fireline intensity mean

Alternative hypothesis:

Treatment fireline intensity mean $\neq$ Control fireline intensity mean

All null hypothesis test results were evaluated at the 95% significance level using the following range **$-2.132 \leq t \leq 2.132$.** If the calculated **t** score falls outside the evaluation range the null hypothesis is rejected. If the test result does not reject the null hypothesis, then it can be inferred that the means of the treatment and control areas are equal and the treatment of areas is not reducing fireline intensities.

Plot data

Data was previously gathered on the treatment and control plots by the Alaska Fire Service as part of the on going experiment for plant regeneration. This data was evaluated to provide stem density per diameter class, tree height per diameter class, height to live crown per diameter class and height to ladder fuel per diameter class. (Appendix F). A photo series[4] was used as a starting point for biomass determination. BS 05 Alaska Black Spruce was used based on photo and overstory table characteristics that were closely related to the control area. The table format in the photo series was kept and expanded to include additional needed values. (Appendix G). The above-mentioned data was used to generate values that were input into tables for the treatment and the control plots outlined below.

[4] Stereo Photo Series for Quantifying Natural Fuels, Volume II: Black Spruce and White Spruce Types in Alaska.

Historical Weather

Historical weather was downloaded for the Fairbanks Remote Automated Weather Station (RAWS) from Kansas City Fire Access Software (KCFAST) and entered into Fire Family Plus. The dates downloaded were May 1st to August 31st, which best represents the fire season in Alaska. The Fairbanks RAWS[5] is approximately 2.56 miles from the treatment area and placed in fuels very similar to the control area. The Fairbanks RAWS had 5 years of data and was used because the next nearest RAWS station, with longer historical data, is 9.16 miles from the treatment plot and located in the open at the Fairbanks International Airport. From this data percentile weather was determined using Fire Family Plus. It has been determined by the Alaska Fire Service community that ignitions do not start when the Fine Fuel Moisture Code (FFMC) is below 80 and starts do not begin to spread until the FFMC has reached 86.[6]

Potential rate of spread and flame length

Norum (1982) provides a way to calculate rate of spread in black spruce/feathermoss forests. Fire behavior fuel model 9 was used to predict rate of spread, with the result multiplied by 1.21.[7] A value of 100 percent was used for the live fuel moisture content in the behavior calculations based on Norum's findings. The 1-hour fuel moisture values were determined using the historical percentile weather data above and the Fire Behavior Field Reference Guide[8] and input into each model to get the resulting values in the table below. 1% and 2% were added to the 1-hour fuel moistures to get the 10-hour and 100-hour fuel moistures respectively.[9] A wind adjustment factor of 0.35 and 0.11 was used for converting the 20 foot wind speed to mid-flame wind speed for the treatment and control areas respectively.[10]

Fuel model 5 was used to predict fireline intensity and can be converted to flame length using Bryam's equation.[11] Entering fuel moisture values derived from the tables in the

[5] Coordinadtes 64 50.817 X 147 36.600
[6] Per conversations with the Alaska State Fuels Management Specialist Kato Howard
[7] Norum, R.A. 1982. p.2
[8] National Wildfire Coordinating Group. 1992. Fuel Moisture, Table A.
[9] Rothermel, R.C. 1983. p.14
[10] Rothermel, R.C. 1983. p.33
[11]Norum, R.A. 1982. p.7

Fire Behavior Field Reference Guide, wind adjustment factors per Rothermel and historical weather generated by Fire Family Plus, fuel model 5 in BEHAVE can be use to produce fireline intensities.

Available Above Ground Mass

Analysis was done to determine the total above ground available fuel for consumption. Roussopoulos et al.[12] provides the regression equation to determine the total foliage (described as all foliage and branches $\leq$1/4" diameter) biomass in spruce.

The equation is;

$$Y = aX^b$$

Where Y = mass in grams and X = basal diameter in centimeters. a and b are the regression equation intercepts where a = 36.288 and b = 2.047.

This equation was accepted with the following resultant R^2 at .95 and a standard error of 42 grams per tree.

Crown bulk density

Crown bulk densities can be easily determined by dividing the total available crown mass by the length of the crown (the height to live crown subtracted from the total height of the tree).

Critical surface fire intensity for initial crown combustion.

Crown fire initiation in a conifer stand is important. Van Wagner (1977) developed some physical criteria for crown fire initiation and spread. Tree crown ignition depends on surface fire intensity and is more difficult to attain as the height of the crown base increases. Another important parameter is foliar moisture content. Using Van Wagner's equation 4, critical surface intensity needed to initiate crowning can be calculated.

$$I_o = (.01 * z (460 + (26 * FMC)))^{3/2}$$

Where z = height to live crown base and FMC = foliar moisture content.[13] The onset of crown combustion should take place when the intensity of the surface fire (I_s),

[12]Roussopoulos, P. J., Loomis, R. M. 1979. p.3
[13]Van Wagner, C.E. 1977. p.24

determined from fire programs like BEHAVE, exceeds I_o. Using the average height to live crown values in meters from the tables in Appendix F for the treatment and the default of .5 meters for the control[14] areas in equation 4 above the critical surface fire intensity for initial crown combustion can be determined.

Class of crown fire

Using bulk density and rate of spread as the limiting factors on whether a crown fire, once initiated, will continue to spread through the crowns or fail is determined by either rate of spread or bulk density falling below a threshold. This level can be determined by Van Wagner's equation 6.[15]

$$Rd = S$$

Where R is the rate of spread in m/sec, d is bulk density in kg/m^3 and S is the mass flow rate of fuel into the crown space in terms of mass per unit cross-sectional area per unit of time, here in $kg/m^2/sec$.

Using Van Wagner's critical spread rate for active crown fire in black spruce (R_o) = 1.11 m/sec and crown bulk density in black spruce (d) = 0.045 kg/m^3, we arrive at a constant value of 0.05 $kg/m^2/sec$ as the critical mass flow rate (S_o) that must be maintained for active crown fire.[16] Equation 6 can be rearranged thus;

$$R_o = S_o/d$$

Using the calculated values from Norum's equation for the treatment and control rates of spread and the values from the treatment and control areas for crown bulk densities from the previous page we can determine if an active crown fire will be achieved under the various percentile weather parameters.

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[14] Per conversations with the Alaska State Fuels Management Specialist Kato Howard.
[15] Van Wagner, C.E. 1977. p.25
[16] Van Wagner, C.E. 1977. p.24

Assumptions and Limitations

1. Control plot is an accurate representation of the treatment plot before manipulation was done.

2. Crown mass calculations, derived from estimates (Roussopoulos, Loomis. 1979), are accurate representations of the available fuel.

3. Fuels inventory of plot data assumed to be 100% accurate.

4. The data used from the Fairbanks Remote Automated Weather Station (RAWS) is an accurate representation of historical weather.

5. The default of .5 meters (1.64 ft.) for height to live crown in control areas of Black Spruce is accurate.

6. The value of 86 for Fine Fuel Moisture Code (FFMC) accurately predicts the spread of ignitions.

7. 50th percentile weather and above is an accurate representation of fire weather days.

Results

Historical Weather

The downloaded weather of May 1st to August 31st from the Fairbanks RAWS was input into Fire Family Plus. Using the Fine Fuel Moisture Code (FFMC) of 86 as a starting point to determine the initiation of ignitions, the following table is generated, where the FFMC code of 86 corresponds with the 50th percentile weather from the Fairbanks RAWS.

Table 1. Percentile weather and associated weather parameters

Percentile Weather	Wet Bulb (^{o}F)	Dry Bulb (^{o}F)	Relative Humidity (%)	Wind speed (mph)
90	62	80	21	5
80	60.7	76	28	4
70	60.1	72	34	4
60	59.1	69	40	3
50	59.2	66	46	3

Potential rate of spread and flame length

Using the historical percentile weather data above and the fuel moisture values and wind adjustment factors outlined in the procedures section for potential rate of spread the following rate of spread values were calculated using fuel model 9 in BEHAVE using Norum's calculations.

Table 2. Treatment rate of spread

Percentile Weather	1 hour fuel moisture	WAF 0.35	ROS Model 9 ch/hr	ROS Model 9 * 1.21 ch/hr	ROS Model 9 * 1.21 m/min	ROS Model 9 * 1.21 m/sec	ROS Model 9 * 1.21 ft/sec
90	3	1.75	2.9	3.5	1.173	0.020	0.064
80	4	1.40	2.1	2.5	0.838	0.014	0.046
70	5	1.40	1.9	2.3	0.771	0.013	0.042
60	6	1.05	1.4	1.7	0.570	0.010	0.031
50	7	1.05	1.3	1.6	0.536	0.009	0.029

Table 3. Control rate of spread

Percentile Weather	1 hour fuel moisture	WAF 0.11	ROS Model 9 ch/hr	ROS Model 9 * 1.21 ch/hr	ROS Model 9 * 1.21 m/min	ROS Model 9 * 1.21 m/sec	ROS Model 9 * 1.21 ft/sec
90	3	0.55	1.4	1.7	0.570	0.010	0.031
80	4	0.44	1.2	1.5	0.503	0.008	0.028
70	5	0.44	1.0	1.2	0.402	0.007	0.022
60	6	0.33	0.9	1.1	0.369	0.006	0.020
50	7	0.33	0.8	1.0	0.335	0.006	0.018

The above fuel moisture values, wind adjustment factors and weather were entered into fuel model 5 of BEHAVE producing the results in table 4.

Table 4. Percentile weather and resulting fireline intensities and flame lengths

Percentile Weather	Treatment Fireline Intensity (btu/ft/sec)	Treatment Flame Length (ft)	Control Fireline Intensity (btu/ft/sec)	Control Flame Length (ft)
90	101	3.8	34	2.3
80	70	3.2	27	2.0
70	62	3.0	23	1.9
60	38	2.4	17	1.6
50	28	2.1	12	1.4

The one sample t-test for means (Appendix D) indicates a value of 59.8 btu/ft/sec for the treatment area and a value of 22.6 btu/ft/sec for the control area. This corresponds to the 69th percentile weather for both the treatment and the control areas.

Generated values for temperature, relative humidity and windspeed from Fire Family Plus for the 69th percentile weather reveals that the values are identical to the 70th percentile weather data above. The corresponding rate of spread and fireline intensities will be used for further analysis.

Available above ground mass

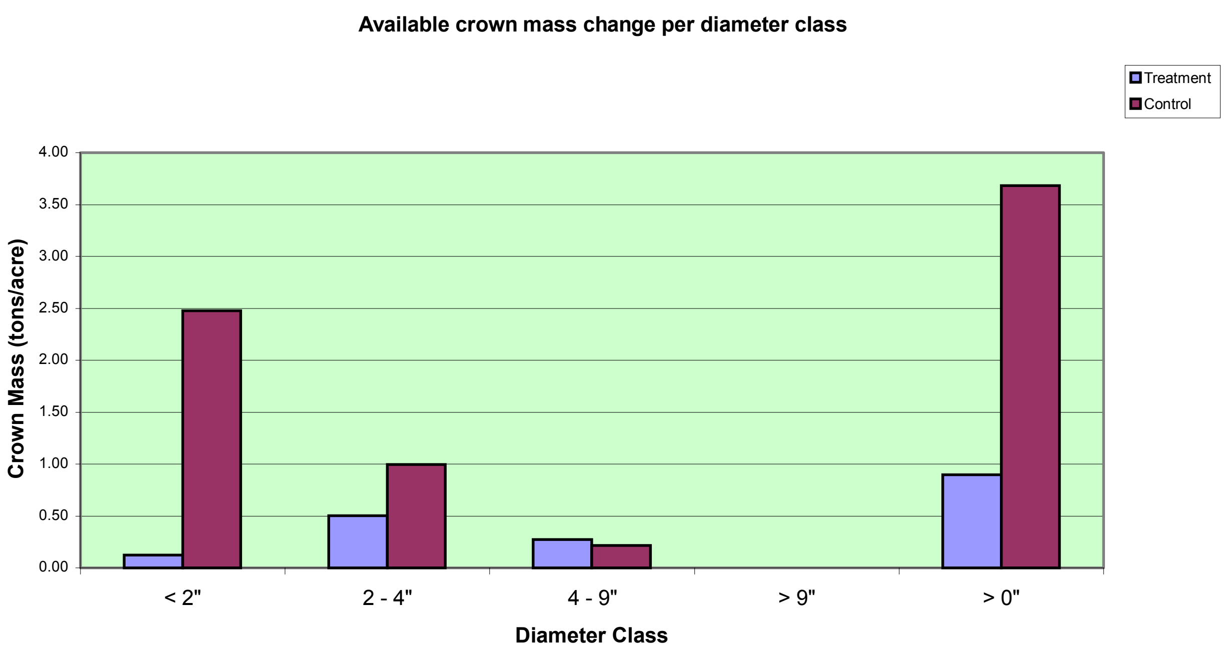
Using the diameters from the various diameter classes derived from the plot data and in the tables in Appendix F for both the treatment and control, available above ground mass was determined using Roussopoulos's equation on page 7. Listed below in the table are the results, converted to tons per acre and pounds per square feet, in relation to diameter class.

Table 5. Above ground mass difference per diameter class

	< 2"	2-4"	4-9"	Total
Control (tons/acre)	2.47	0.99	0.21	3.68
Control (lbs/ft^2)	0.113	0.045	0.010	0.169
Treatment (tons/acre)	0.12	0.50	0.27	0.90
Treatment (lbs/ft^2)	0.006	0.023	0.012	0.041
Reduction %	95.1	49.5	+ 16.7	75.5

The result was the $\leq$1/4" biomass being reduced from 3.68 tons/acre (control) to 0.90 tons/acre (treatment) for an overall reduction in available above ground mass of over 75% as figure A shows.

Figure A



Crown bulk densities

Using the crown mass numbers from table 5 and the average crown height from the plot data in Appendix F for the treatment plot and the default of .5 meters for the control we can determine the average crown length. Crown bulk densities can then be calculated for both the treatment and control areas.

Table 6. Treatment crown bulk densities per diameter class

	≤ 2"	2 – 4"	4 – 9"	> 9"	Total
Crown mass (tons/acre)	0.12	0.50	0.27	0.00	0.90
Crown mass (kg/m^2)	0.03	0.11	0.06	0.00	0.20
Average live crown length (meters)	2.18	3.67	6.91	0.00	3.57
Crown bulk density (kg/m^3)	0.013	0.031	0.009	0.000	0.053

Table 7. Control crown bulk densities per diameter class

	≤ 2"	2 – 4"	4 – 9"	> 9"	Total
Crown mass (tons/acre)	2.48	0.99	0.21	0.00	3.68
Crown mass (kg/m^2)	0.55	0.22	0.05	0.00	0.83
Average live crown length (meters)	2.76	4.40	8.80	0.00	3.25
Crown bulk density (kg/m^3)	0.199	0.050	0.006	0.000	0.255

The crown bulk densities calculated in the tables 6 and 7 show that the crown bulk density has been reduced from 0.255 kg/m^3 in the control to 0.053 kg/m^3 in the treatment for an overall reduction of 79%.

Critical surface fire intensity for initial crown combustion

Treatment	**Control**
$I_o = (0.01*1.41(460 +(26 * 100)))^{3/2}$	$I_o = (0.01*0.50(460 +(26 * 100)))^{3/2}$
I_o = 283.4 kW/m	I_o = 59.8 kW/m
I_o = 81.81 btu/ft/sec[17]	I_o = 17.26 btu/ft/sec[17]

Using Byrum's equation ($.45(I_B)^{.46}$) and the above intensities we can then calculate the flame length required to initiate crowning. They are 3.41 ft. for the treatment area and 1.67 ft. for the control area. Comparing these values with the values predicted for the average mean fire day (70th percentile weather in Table 4), using fuel model 5 in BEHAVE, the treatment (flame length 3.0 feet) does not attain the required flame length while the control (flame length 1.9 feet) does attained the required flame length to initiate crown combustion.

Class of crown fire

Using the values from the treatment and control areas for crown bulk densities from Tables 6 and 7 we can determine if an active crown fire will be achieved under the different percentile weather parameters using 0.05 kg/m^2/sec as the constant for S_o, with the equation;

$$R_o = S_o/d$$

[17] Per conversion sheet. Appendix H

Table 8. Critical rate of spread for treatment and control

	Crown Bulk Density (kg/m^3)	Critical Rate of Spread (m/sec)	Critical Rate of Spread (ch/hr)
Treatment	0.053	0.94	168.76
Control	0.255	0.20	35.08

As can be seen in table 8 the critical spread rate for an active crown fire was not met in either the treatment or the control cases. The critical spread rate for the treatment being 168.76 chains per hour and 35.08 chains per hour for the control.

Since the surface intensity (I_s) has exceeded the critical surface intensity in the control needed to initiate crowning (I_o), crowning will occur but as a passive crown fire, since the critical spread for active crown fire has not been met. The crown phase will remain completely dependant on the surface fire and whose spread rate will control the whole fire, but the intensity of the whole fire will be reinforced by the crown combustion.

Using Bryam's equation for fire intensity;

$$I_B = 8000 * \text{fuel consumed } (lbs/ft^2) * \text{ROS } (ft/sec)$$

and using the calculations done in Table 5 and the rates of spread calculated in Table 5 using Norum's equation the intensity added by the crown fire can be determined.

The treatment crown intensity has not been met and therefore the intensity level for the surface fire remains the same at 62 btu/ft/sec.

The control crown intensity = 8000 * 0.169 (lbs/ft^2) * 0.022 (ft/sec) = 29.74 btu/ft/sec will be added to the control surface intensities, calculated by BEHAVE, to calculate the total fireline intensity level for control area.

Table 9. Total fireline intensity for treatment and control

	Surface Fire Intensity (btu/ft/sec)	Crown Fire Intensity (btu/ft/sec)	Total Fire Intensity (btu/ft/sec)
Treatment	62	0	62
Control	23	30	53

One sample t-test for means

Using the calculated values for fireline intensities from table 9 for the treatment and the control the differences can be determined (Appendix D) and are summarized below.

Mean = 37.2

Standard deviation = 20.22

$\alpha = .05$

Confidence interval = $-2.132 \leq t \leq 2.132$

$t = 4.11$

Since $t = 4.11$ exceeds 2.132, the null hypothesis must be rejected.

Conclusion

The results of this study conclude with 95% confidence that a significant difference exists between the mean total fire intensity of the treatment and control areas, with an increase on an average day from the control area (53 btu/ft/sec) to the treatment area (62 btu/ft/sec). While this was a relatively minor increase in fireline intensity of 17% fire intensities remained in the range of human extinguishment (less than 100 btu/ft/sec). On a 90th percentile day fire intensities increased to 122 btu/ft/sec in the treatment area, 60 % greater than in the control, which takes the treatment area out of the range of human effectiveness (Appendix E).

The effectiveness of shaded fuel breaks remains a subject of debate in the fire community. This paper looked at crown fire initiation which black spruce is exceptionally prone to. The treatment did increase the percentile weather required to initiate crown combustion, although crown combustion did still occur in both the treatment and the control. Treatment not only decreases crown fire initiation but also aids in suppression efforts by opening the canopy up making it more available to retardant and helicopter bucket drops.

The reduction of crown bulk in the treatment did not mitigate crown combustion completely but it did significantly increase the critical rate of spread required to achieve an active crown fire from 35.1 chains per hour to 168.8 chains per hour.

The results of the BEHAVE runs clearly show that for the given weather parameters generated by Fire Family Plus the treatment area had significantly more fire intensity than the control area. This is due primarily by the 20 foot winds being able to penetrate the less dense canopy cover thereby increasing the mid-flame wind speed. This was found to be true of the weather taken by the portable weather stations erected in both treatment and control areas during the 2002 summer (Appendix C). Evaluating the data generated from the weather collected by the weather stations for fuel moisture codes this can be seen due to the fact that the moisture codes for the corresponding plots did not deviate from each other significantly, thus having minimal effect on fire intensity differences.

As Appendix C shows, the fuel moisture codes calculated for the associated fuel groups in the Canadian Forest Fire Danger Rating System (CFFDRS), little variance is seen between the treatment and the control areas. The greatest difference is in the wind data taken from the plots. By opening up the canopy, the wind can now penetrate better thus increasing both fire intensities and rate of spread. This could be seen in the values produced by the BEHAVE program using the wind reduction factors. With all else being equal, the treatment area generated greater fire intensity and rate of spread values.

Suggestions for the future:

Analysis for this project was done on only a 4 foot prune height. More studies with varying prune heights needs to be done. One such study is being done in the Tanacross Hazard Fuel Reduction Project where the pruned height exceeded 4 feet.[18] Preliminary results from this study will be available in the fall of 2003.

Fuel treatments can be measured by crown bulk density calculations as done in this project but it is still unknown what the long term effects of these treatments will have on the permafrost layer and what types of vegetation regeneration will result. The Fuels Demo project[19] plots used in this study are currently researching this vegetation change.

[18] Project initiated by Alaska Fire Service Fuels Management Specialists Mark Musitano and Fred Hernandez.

[19] Alaska Fire Service Fire Ecologist Randi Jandt and Tanana Chiefs Conference, Inc. Forester Dr. Bob Ott

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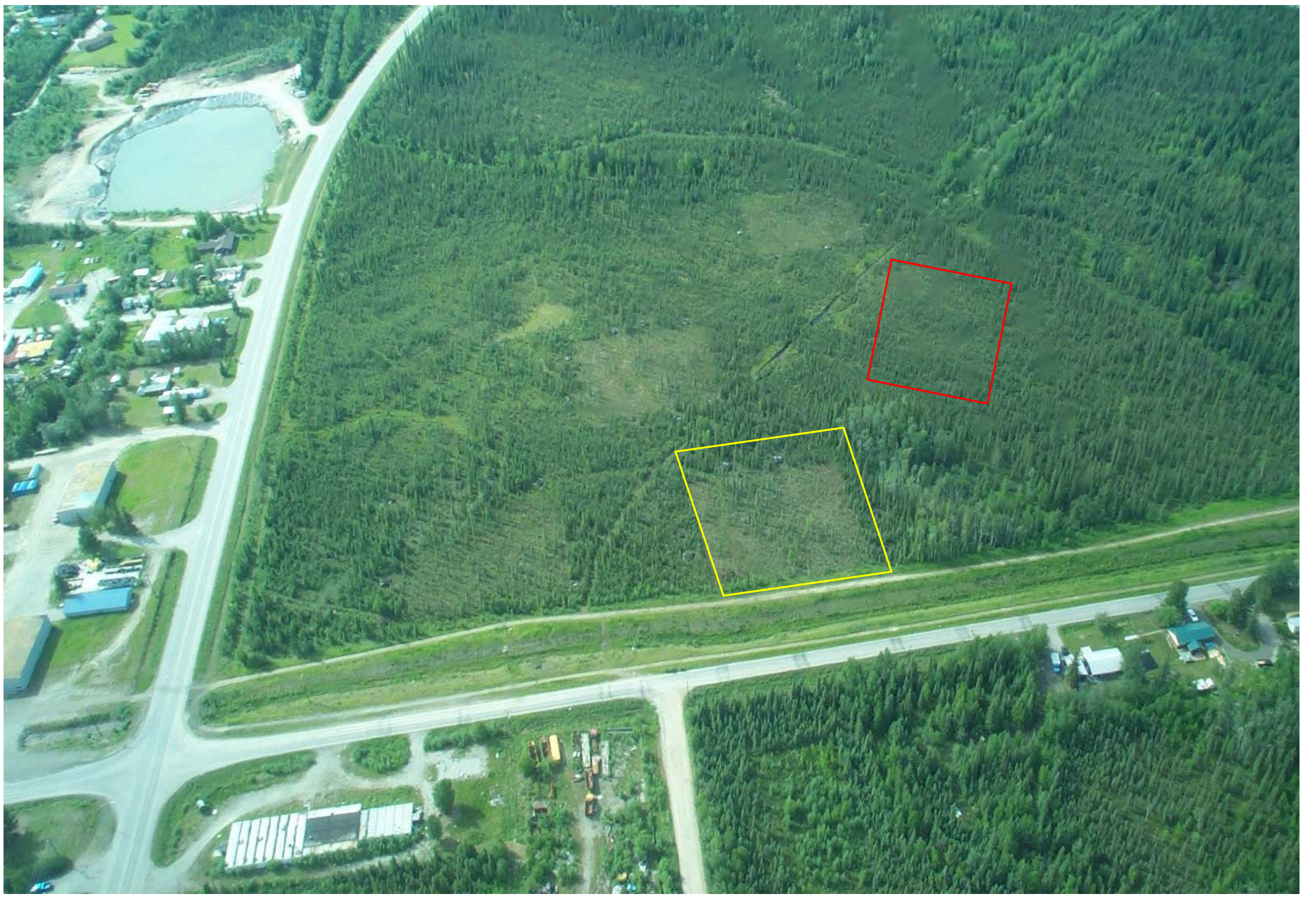
Various excerpts from CFFDRS course in 1996.

Appendix A

Aerial view of treatment and control areas



Treatment

Control

↓ North

Appendix B

Hobo™ weather station setup in treatment area

Component specifications

Temperature sensor	Range: -40^o to 167^o F ($\pm$ 1.3^o @ 77^o F)
Relative Humidity sensor	Range: 0 to 100% ($\pm$ 3% @ 32^o to 122^o F)
Anemometer	Range: 0 to 100 mph ($\pm$ 4% of reading)
Rain Sensor	Range: 0 to 5 inches per hour ($\pm$ 0.01 inches)

Appendix C

Canadian Fire Danger Rating System

The Canadian Fire Danger Rating System (CFFDRS) has been adopted by most of the fire management agencies through out the state of Alaska. The CFFDRS incorporates weather, fuel moisture, fuel type and fire behavior into one complete system. The ultimate goal of the system is to produce a fire danger rating system such that any given index value will always represent the same fire behavior regardless of the preceding weather history (Van Wagner 1970). The CFFDRS is made up of two sub-systems, the Fire Weather Index (FWI) and the Fire Behavior Prediction (FBP). The Fire Weather Index (FWI) system consists of six standard components, three moisture codes and three fire behavior indexes, all listed below. The CFFDRS system has in 16 fuel types, 5 of which are used in Alaska. As stated earlier, I concentrated on the fuel type identified as C-2 (Boreal Spruce) of the CFFDRS models, since it is the problem fuel type in Alaska and where shaded fuel breaks are generally constructed.

Moisture codes:

Code	Represents	Time Lag*	24 hr. rainfall required to lower value
FFMC Fine Fuel Moisture	Surface Litter	2/3 day	0.6 mm
DMC Duff Moisture	5-10 cm Duff	12 days	1.5 mm
DC Drought Code	10-20 cm. Duff	52 days	2.9 mm

*Time lag refers to the time required for fuel to lose 2/3 of its moisture under average drying conditions, i.e., 21 degrees Celsius and 45% R.H. (S-390 (B.C.) Fire behavior Prediction 1987).

Behavior codes:

ISI – Initial Spread Index Represents the relative fire spread expected immediately after ignition.
BUI – Build Up Index Represents the total amount of fuel available for combustion, a useful guide in determining mop-up requirements.
FWI – Fire Weather Index Represents the potential fire intensity, therefore is useful in determining fire control requirements.

(S-390 (B.C.) Fire behavior Prediction 1987)

Fire Behavior Prediction System (FBP)

The FBP uses code values from the FWI system – gives adjustments for time, fuel and topography specific to the fire location – and provides information that is useful in actually predicting fire behavior and spread rates.

C-2 boreal spruce

Equilibrium rate of spread (m/min) and fire intensity class

BUI

ISI	0-20	21-30	31-40	41-60	61-80	81-120	121-160	161-200
1	0.1	0.3	0.4	0.5	0.5	0.6	0.6	0.6
2	0.3	0.9	1	1	1	2*	2*	2*
3	0.6	2	2	2*	3*	3*	3*	3*
4	0.9	3	3*	4*	4*	4*	4*	5*
5	1	3*	4*	5*	5*	6*	6*	6*
6	2	4*	5*	6*	7*	7*	8*	8*
7	2	5*	7*	8*	9*	9*	10*	10*
8	2	7*	8*	9*	10*	11	12	12
9	3	8*	9*	11*	12	13	14	14
10	3	9*	11*	12	14	15	16	16
11	4	10*	12	14	16	17	18	18
12	4	11*	14	16	17	19	20	20
13	4	12	15	17	19	21	22	22
14	5	13	16	19	21	23	24	25
15	5	15	18	21	23	25	26	27
16	6*	16	19	22	25	27	28	29
17	6*	17	21	24	27	29	30	31
18	6*	18	22	26	28	31	32	33
19	7*	19	23	27	30	33	34	35
20	7*	20	25	29	32	34	36	37
21-25	8*	24	29	34	37	40	42	43
26-30	10*	29	35	41	46	49	52	53
31-35	12*	34	41	48	53	57	60	62
36-40	14*	39	47	54	60	65	68	70
41-45	15	43	52	60	66	72	75	78
46-50	16	46	56	65	72	78	82	84
51-55	17	49	60	70	77	83	87	90
56-60	18	52	64	74	82	88	92	95
61-65	19	55	67	77	85	92	97	100
66-70	20	57	69	80	89	96	101	104

10 - 500 kW/m
500 - 2,000
2,000 - 4,000
4,000 - 10,000
> 10,000

Type of fire: surface intermittent crown* continuous crown

Calculated Moisture Codes

From daily observations, taken at solar noon (1300 Alaska Daylight Time), of weather including temperature (^{o}C), relative humidity (%), wind (km/hr) and rain (mm), calculation of the components of the FWI system can be accomplished. Starting with a derived value for each moisture code (Fairbanks RAWS was used) the previous days value is used to calculate today's value based on solar noon weather. Throughout the summer a running total of each code is kept. Inputs of warm dry weather increase the number (code). Inputs of cool weather decrease the codes. Rain has a decreasing effect on all codes, varying with amount.

Below are the calculated values for both the treatment and control areas using the Tables for the Canadian Forest Fire Weather Index System.

Treatment

Start with RAWS	55	60	290			
Date_Time	FFMC	DMC	DC	ISI	BUI	FWI
6/21/02 13:00	69	62	296	1.0	81	4
6/22/02 13:00	82	65	302	1.5	84	7
6/23/02 13:00	85	68	309	2.0	88	9
6/24/02 13:00	85	70	316	2.5	88	10
6/25/02 13:00	48	41	309	0.0	62	0
6/26/02 13:00	71	44	316	0.5	67	1
6/27/02 13:00	86	48	324	3.0	71	11
6/28/02 13:00	84	52	332	2.0	77	8
6/29/02 13:00	85	54	339	2.5	77	10
6/30/02 13:00	88	58	346	4.0	82	14
7/1/02 13:00	62	42	344	0.5	64	1
7/2/02 13:00	12	20	287	0.0	33	0
7/3/02 13:00	7	14	291	0.0	25	0
7/4/02 13:00	40	8	262	0.0	15	0
7/5/02 13:00	12	4	250	0.0	8	0
7/6/02 13:00	19	5	256	0.0	10	0
7/7/02 13:00	44	7	263	0.0	13	0
7/8/02 13:00	65	10	271	0.5	18	0
7/9/02 13:00	81	13	279	1.5	23	2
7/10/02 13:00	86	16	287	3.0	27	6
7/11/02 13:00	89	20	295	4.0	33	9
7/12/02 13:00	86	23	303	3.0	40	8
7/13/02 13:00	88	26	311	3.0	43	8
7/14/02 13:00	86	28	318	3.0	47	8
7/15/02 13:00	86	30	325	3.0	47	8
7/16/02 13:00	89	33	333	4.0	52	11
7/17/02 13:00	91	37	342	6.0	60	17
7/18/02 13:00	91	41	350	6.0	64	18

7/19/02 13:00	89	43	358	4.0	64	13
7/20/02 13:00	79	44	364	1.0	70	4
7/21/02 13:00	85	47	372	2.0	70	8
7/22/02 13:00	89	50	380	4.0	74	14
7/23/02 13:00	89	53	388	4.0	79	14
7/24/02 13:00	50	26	338	0.0	44	0
7/25/02 13:00	28	16	328	0.0	28	0
7/26/02 13:00	43	17	334	0.0	31	0
7/27/02 13:00	42	18	340	0.0	31	0
7/28/02 13:00	58	13	324	0.5	24	1
7/29/02 13:00	76	16	331	1.0	28	2
7/30/02 13:00	83	19	339	1.5	34	3
7/31/02 13:00	91	23	347	6.5	40	14.5
8/1/02 13:00	92	27	354	7.0	44	16
8/2/02 13:00	90	30	361	4.0	49	11
8/3/02 13:00	90	33	369	4.0	53	12
8/4/02 13:00	88	35	376	3.0	57	9
8/5/02 13:00	90	38	383	5.0	61	15
8/6/02 13:00	63	27	372	0.5	44	1
8/7/02 13:00	17	15	344	0.0	28	0
8/8/02 13:00	17	16	349	0.0	28	0
8/9/02 13:00	31	12	349	0.0	22	0
8/10/02 13:00	52	13	354	0.0	24	0
8/11/02 13:00	65	14	360	0.5	26	1
8/12/02 13:00	70	15	365	0.5	28	1
8/13/02 13:00	79	16	370	1.5	28	3
8/14/02 13:00	82	17	375	1.5	31	3
8/15/02 13:00	84	19	381	2.5	35	6
8/16/02 13:00	77	20	386	1.0	35	2

Treatment

Start with RAWS	78	4	218			
Date_Time	FFMC	DMC	DC	ISI	BUI	FWI
8/27/02 13:00	81	5	224	1.5	9	1
8/28/02 13:00	66	4	230	0.5	8	0
8/29/02 13:00	67	5	235	0.5	9	0
8/30/02 13:00	76	6	241	1.0	11	1
8/31/02 13:00	77	7	247	1.0	13	1
9/1/02 13:00	75	7	251	1.0	13	1
9/2/02 13:00	76	7	254	1.0	13	1
9/3/02 13:00	59	6	258	0.5	11	0
9/4/02 13:00	60	6	261	0.5	11	0
9/5/02 13:00	35	4	240	0.0	8	0
9/6/02 13:00	37	4	244	0.0	8	0
9/7/02 13:00	47	4	248	0.0	8	0
9/8/02 13:00	59	5	252	0.5	10	0
9/9/02 13:00	65	5	255	0.5	10	0
9/10/02 13:00	66	5	257	0.5	10	0
9/11/02 13:00	75	5	260	1.0	10	1
9/12/02 13:00	82	6	264	2.0	11	2
9/13/02 13:00	83	7	268	2.0	13	2
9/14/02 13:00	86	9	272	2.5	17	3
9/15/02 13:00	86	10	276	2.5	18	4
9/16/02 13:00	81	10	279	1.5	18	2
9/17/02 13:00	81	10	282	1.5	18	2
9/18/02 13:00	73	10	285	1.0	18	1
9/19/02 13:00	76	10	287	1.0	18	1

9/20/02 13:00	74	10	289	1.0	18	1
9/21/02 13:00	75	10	291	1.0	18	1
9/22/02 13:00	82	11	295	1.5	20	2
9/23/02 13:00	85	13	299	2.0	23	3
9/24/02 13:00	84	13	302	2.0	24	4
9/25/02 13:00	83	13	306	1.5	24	3
9/26/02 13:00	53	8	281	0.5	15	0
9/27/02 13:00	57	8	284	0.5	15	0
9/28/02 13:00	30	4	273	0.0	8	0
9/29/02 13:00	22	2	273	0.0	4	0
9/30/02 13:00	22	2	276	0.0	4	0
10/1/02 13:00	23	0	279	0.0	0	0
10/2/02 13:00	35	0	282	0.0	0	0
10/3/02 13:00	47	0	284	0.0	0	0
10/4/02 13:00	52	0	286	0.0	0	0
10/5/02 13:00	56	0	288	0.5	0	0
10/6/02 13:00	67	0	290	0.5	0	0
10/7/02 13:00	31	0	292	0.0	0	0
10/8/02 13:00	43	0	294	0.0	0	0
10/9/02 13:00	41	0	296	0.0	0	0
10/10/02 13:00	48	0	298	0.0	0	0

Control

Start with RAWS	55	60	290			
Date_Time	FFMC	DMC	DC	ISI	BUI	FWI
6/21/02 13:00	69	62	295	1.0	81	4
6/22/02 13:00	82	65	302	1.5	84	77
6/23/02 13:00	87	68	309	3.0	88	12
6/24/02 13:00	87	71	316	3.0	92	13
6/25/02 13:00	56	41	309	0.5	62	1
6/26/02 13:00	74	44	316	1.0	67	4
6/27/02 13:00	86	48	324	2.5	71	9
6/28/02 13:00	84	52	332	2.0	77	8
6/29/02 13:00	85	55	339	2.5	77	10
6/30/02 13:00	87	59	346	3.0	82	11
7/1/02 13:00	60	42	344	0.5	62	1
7/2/02 13:00	12	20	287	0.0	33	0
7/3/02 13:00	7	14	291	0.0	25	0
7/4/02 13:00	32	8	262	0.0	15	0
7/5/02 13:00	7	4	250	0.0	8	0
7/6/02 13:00	14	5	256	0.0	10	0
7/7/02 13:00	39	7	263	0.0	13	0
7/8/02 13:00	70	10	271	0.5	18	0
7/9/02 13:00	82	10	279	1.5	18	2
7/10/02 13:00	82	13	287	1.5	23	2
7/11/02 13:00	84	17	295	2.0	30	4
7/12/02 13:00	84	20	303	2.0	34	4
7/13/02 13:00	87	23	311	3.0	40	8
7/14/02 13:00	87	25	318	3.0	43	8
7/15/02 13:00	87	28	326	3.0	47	8

7/16/02 13:00	89	32	334	4.0	52	11
7/17/02 13:00	90	36	343	4.0	56	12
7/18/02 13:00	91	40	352	5.0	64	15
7/19/02 13:00	90	43	360	4.0	65	13
7/20/02 13:00	78	44	366	1.0	70	4
7/21/02 13:00	85	47	374	2.0	70	8
7/22/02 13:00	90	51	382	4.0	74	14
7/23/02 13:00	90	55	390	4.0	79	14
7/24/02 13:00	50	28	351	0.0	48	0
7/25/02 13:00	24	18	343	0.0	31	0
7/26/02 13:00	28	19	349	0.0	34	0
7/27/02 13:00	33	20	355	0.0	34	0
7/28/02 13:00	35	13	338	0.0	24	0
7/29/02 13:00	67	16	346	0.5	28	1
7/30/02 13:00	79	20	354	1.0	34	2
7/31/02 13:00	89	24	362	5.0	41	12
8/1/02 13:00	92	28	369	6.0	49	15
8/2/02 13:00	92	31	376	6.0	53	16
8/3/02 13:00	92	35	384	6.0	57	16
8/4/02 13:00	89	38	391	4.0	61	12
8/5/02 13:00	90	41	399	5.0	65	15
8/6/02 13:00	63	27	386	0.5	44	1
8/7/02 13:00	17	15	358	0.0	28	0
8/8/02 13:00	12	16	363	0.0	28	0
8/9/02 13:00	31	12	364	0.0	22	0
8/10/02 13:00	52	13	369	0.0	24	0
8/11/02 13:00	65	14	375	0.5	26	1
8/12/02 13:00	70	15	380	0.5	28	1
8/13/02 13:00	79	16	385	1.5	28	3
8/14/02 13:00	82	17	390	1.5	31	3
8/15/02 13:00	85	19	396	2.0	35	5
8/16/02 13:00	78	20	401	1.0	35	2

Control

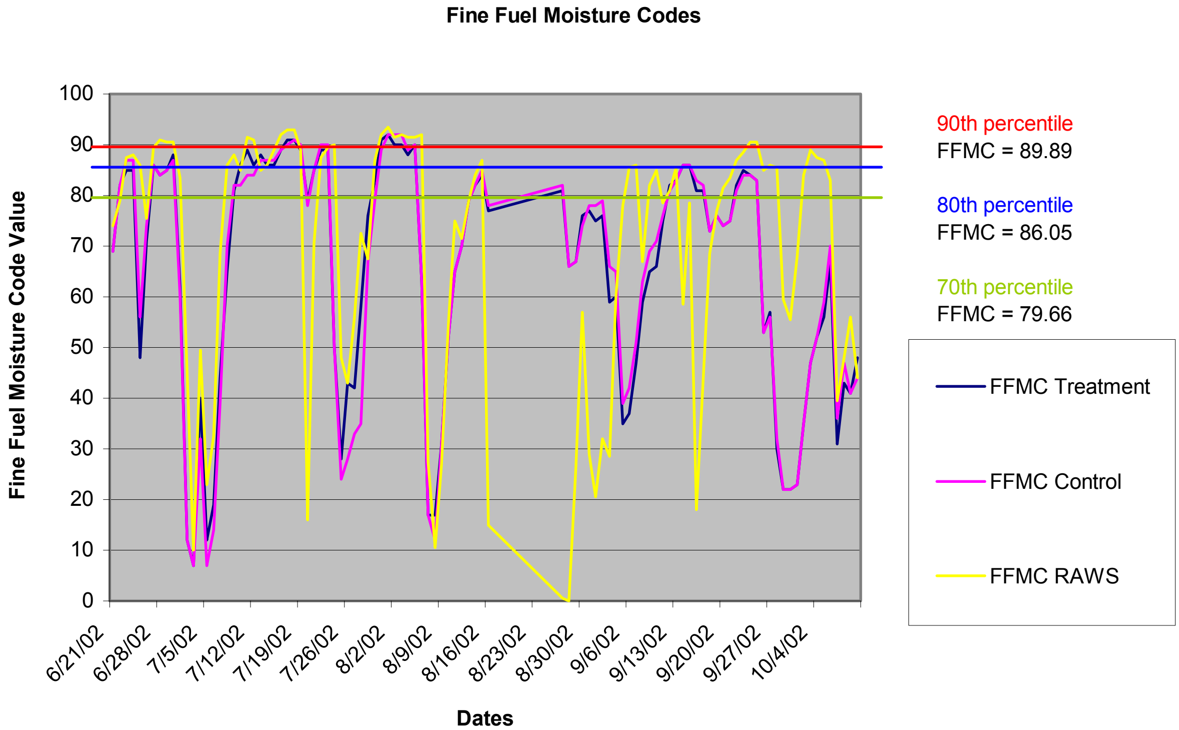
Start with RAWS	78	4	218			
Date_Time	FFMC	DMC	DC	ISI	BUI	FWI
8/27/02 13:00	82	5	224	1.5	9	1
8/28/02 13:00	66	4	230	0.5	8	0
8/29/02 13:00	67	5	235	0.5	9	0
8/30/02 13:00	74	6	241	1.0	11	1
8/31/02 13:00	78	7	247	1.0	13	1
9/1/02 13:00	78	7	251	1.0	13	1
9/2/02 13:00	79	7	254	1.0	13	1
9/3/02 13:00	66	6	258	0.5	11	0
9/4/02 13:00	65	6	261	0.5	11	0
9/5/02 13:00	39	4	240	0.0	8	0
9/6/02 13:00	42	4	244	0.0	8	0
9/7/02 13:00	51	4	248	0.0	8	0
9/8/02 13:00	63	5	252	0.5	10	0
9/9/02 13:00	69	5	255	0.5	10	0
9/10/02 13:00	71	5	257	0.5	10	0
9/11/02 13:00	76	5	260	1.0	10	1
9/12/02 13:00	81	6	264	1.5	11	1
9/13/02 13:00	83	7	268	2.0	13	2
9/14/02 13:00	86	9	272	2.5	17	3
9/15/02 13:00	86	10	276	2.5	18	4
9/16/02 13:00	83	10	279	1.5	18	2

9/17/02 13:00	82	10	282	1.5	18	2
9/18/02 13:00	73	10	286	1.0	18	1
9/19/02 13:00	76	10	289	1.0	18	1
9/20/02 13:00	74	10	291	1.0	18	1
9/21/02 13:00	75	10	293	1.0	18	1
9/22/02 13:00	81	12	297	1.5	22	2
9/23/02 13:00	84	14	301	2.0	25	4
9/24/02 13:00	84	14	304	2.0	25	4
9/25/02 13:00	83	14	307	1.5	25	3
9/26/02 13:00	53	8	282	0.5	15	0
9/27/02 13:00	56	8	285	0.5	15	0
9/28/02 13:00	32	4	288	0.0	8	0
9/29/02 13:00	22	2	288	0.0	4	0
9/30/02 13:00	22	2	291	0.0	4	0
10/1/02 13:00	23	0	294	0.0	0	0
10/2/02 13:00	35	0	296	0.0	0	0
10/3/02 13:00	47	0	298	0.0	0	0
10/4/02 13:00	52	0	300	0.0	0	0
10/5/02 13:00	59	0	302	0.5	0	0
10/6/02 13:00	70	0	304	0.5	0	0
10/7/02 13:00	36	0	301	0.0	0	0
10/8/02 13:00	47	0	303	0.0	0	0
10/9/02 13:00	41	0	305	0.0	0	0
10/10/02 13:00	44	0	307	0.0	0	0

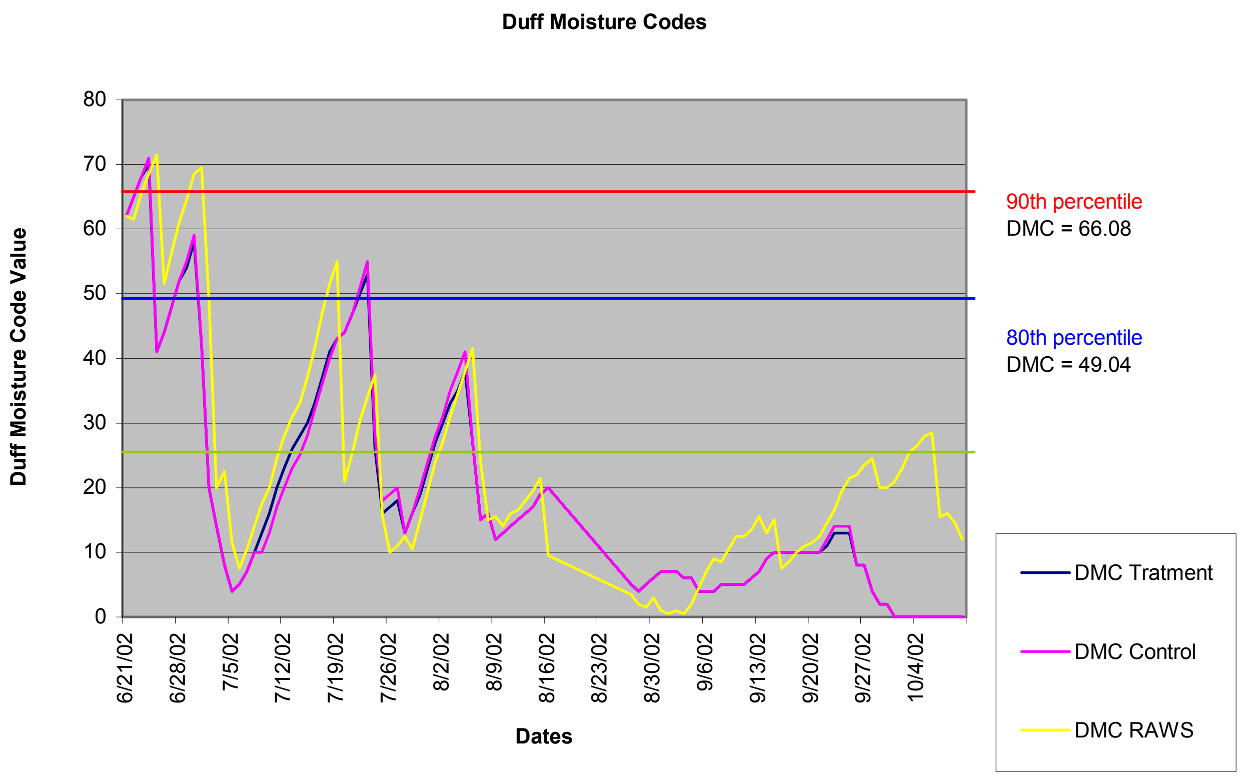
Charts of Moisture Codes

Below are the Fine Fuel Moisture codes, Duff Moisture Codes and the Drought Codes charted with the Fairbanks RAWS data at 1300 (ADT).

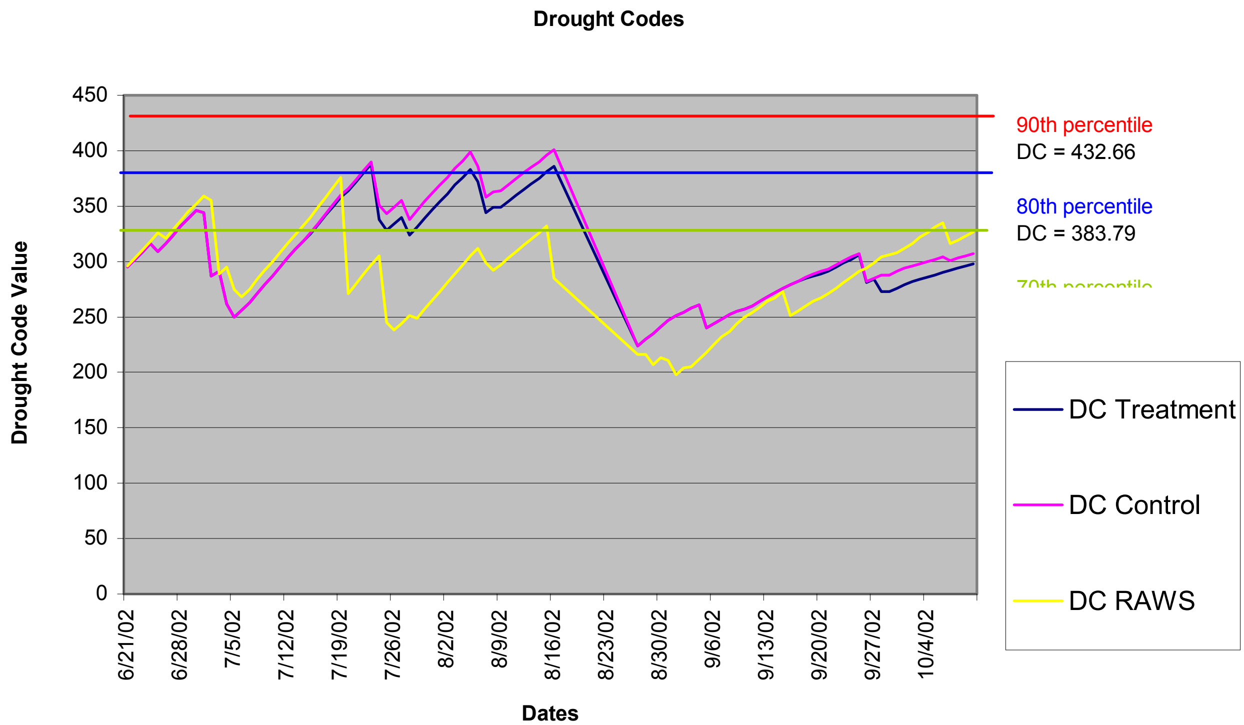
Fine Fuel Moisture Codes

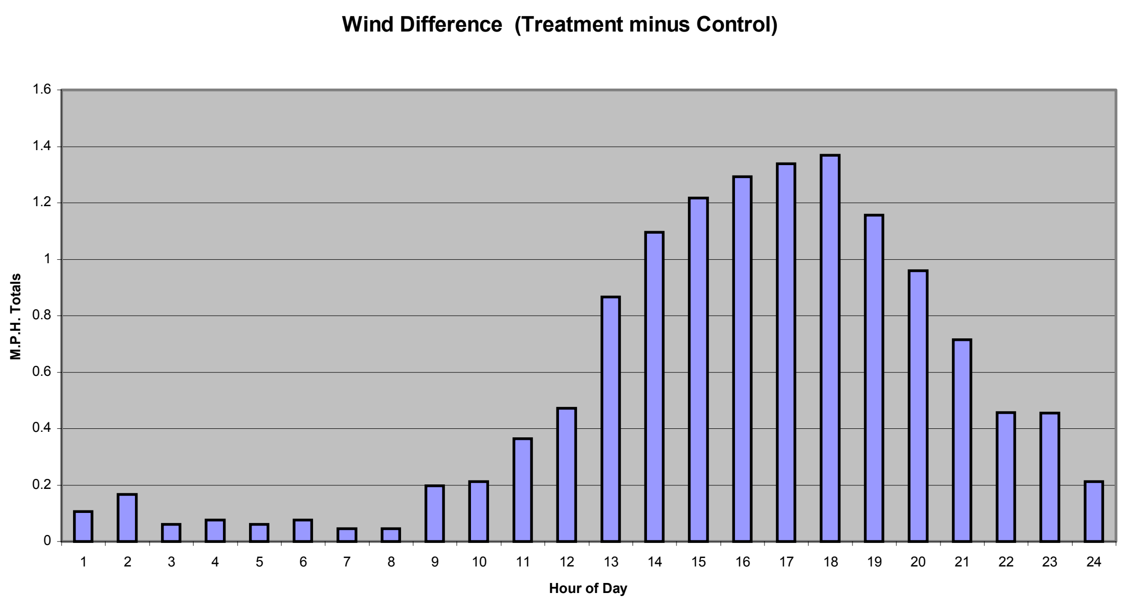


Duff Moisture Codes



Drought Codes





Appendix D

Percentile Weather	Treatment intensities minus Control intensities	Difference
90	101 – 34	67
80	70 – 27	43
70	62 – 23	39
60	38 –17	21
50	28 -12	16

Mean = 186/5 = 37.2

Standard deviation = square root of (1636.8/4) = 20.22

$t = 37.2 / (20.22 / \sqrt{5}) = 37.2 / 9.04 = 4.11$

Appendix E

Bryam's equation using 90th percentile weather

	Surface Fire Intensity (btu/ft/sec)	Crown Fire Intensity (btu/ft/sec)	Total Fire Intensity (btu/ft/sec)
Treatment	101	21	122
Control	34	38	72

Appendix F

Tagged Trees

Site: Fort Wainwright
RX: Post-treatment
Date: September and October 2001

Note: Plots are each 1 acre square, 209 ft. by 209 ft. There are five subplots, each 30 ft. by 30 ft., in a 1 acre plot. The location of the five subplots in a 1 acre plot are as follows: subplot 1 is 49 ft. at 135° from the NW corner; subplot 2 is 49 ft. at 225° from the NE corner; subplot 3 is 35 ft. at 135° from the SE corner of subplot 1, which places it in the middle of the 1 acre plot; subplot 4 is 49 ft. at 45° from the SW corner; subplot 5 is 49 ft. at 315° from the SE corner. There are three size classes, ≤ 2" DBH, 2.1 - 4" DBH, and > 4" DBH. Five trees, per size class, are tagged around the center of each subplot. The Live Crown Height is the vertical distance from the ground to the bottom of the live crown. The Fuel Ladder Height is the vertical distance from the ground to the bottom of any ladder fuel, dead or live.

Plot	Subplot	Tree	Spp	DBH(in)	Height (ft)	Ht to Live Crown (ft)	Ht to fuel ladder (ft)
10P	1	753	PIMA	2.80	15.3	3.1	3.1
10P	1	752	PIMA	1.97	14.4	8.3	3.0
10P	1	751	PIMA	1.91	13.0	5.0	5.0
10P	1	750	PIMA	2.28	15.7	5.0	5.0
10P	1	749	PIMA	1.72	15.6	5.8	5.1
10P	1	748	PIMA	2.11	13.3	1.5	0.0
10P	1	747	PIMA	1.42	10.8	4.5	3.5
10P	1	746	PIMA	2.18	11.6	7.2	4.5
10P	1	745	PIMA	1.95	14.9	5.2	5.2
10P	1	744	PIMA	0.90	7.9	3.1	3.0
10P	2	743	PIGL	4.70	31.0	5.0	5.0
10P	2	742	PIMA	1.75	10.1	3.8	3.8
10P	2	741	PIMA	2.95	20.4	4.7	4.7
10P	2	740	PIMA	4.00	23.9	4.8	4.8
10P	2	739	PIGL	4.28	23.2	5.0	5.0
10P	2	738	PIMA	2.09	14.4	3.0	3.0
10P	2	737	PIMA	2.65	17.8	5.1	4.5
10P	2	736	PIMA	2.10	13.4	5.5	5.0
10P	2	735	PIMA	2.40	13.4	4.7	4.7
10P	3	734	PIMA	2.50	17.5	6.0	6.0
10P	3	733	PIMA	3.42	24.2	4.8	4.8
10P	3	732	PIGL	5.70	29.3	5.5	4.0
10P	3	731	PIMA	2.27	14.9	5.0	4.5

10P	3	730	PIMA	2.20	16.2	6.1	5.9
10P	3	729	PIMA	2.77	19.2	7.5	5.5
10P	3	728	PIMA	2.46	17.8	4.5	4.5
10P	3	727	PIMA	1.60	13.2	5.1	5.0
10P	4	726	PIMA	1.87	11.9	3.2	3.2
10P	4	725	PIMA	1.95	15.4	3.7	3.7
10P	4	724	PIMA	2.23	15.3	5.0	4.5
10P	4	723	PIMA	4.90	25.1	4.5	4.0
10P	4	722	PIMA	2.02	13.3	4.2	3.6
10P	4	721	PIMA	2.54	17.5	2.2	2.2
10P	4	720	PIMA	5.95	32.3	4.0	4.0
10P	4	719	PIMA	2.80	16.9	4.5	3.5
10P	4	718	PIMA	3.39	20.4	3.0	2.9
10P	4	717	PIMA	1.11	7.8	2.2	2.2
10P	5	716	PIMA	1.42	10.9	5.5	4.0
10P	5	715	PIMA	0.89	6.9	3.0	3.0
10P	5	714	PIMA	2.30	9.8	5.8	3.3
10P	5	713	PIMA	1.20	8.9	5.2	4.0
10P	5	712	PIMA	1.55	11.2	3.9	3.9
10P	5	711	PIMA	1.76	13.5	4.5	3.9
10P	5	710	PIMA	2.92	20.3	4.8	4.0
10P	5	709	PIMA	3.60	25.6	3.8	3.0
C	1	666	PIGL	3.84	20.3	9.2	0.0
C	1	665	PIMA	0.90	8.0	2.0	0.0
C	1	664	PIGL	3.15	17.6	4.2	0.0
C	1	663	PIMA	1.65	13.9	10.0	0.0
C	1	662	PIGL	2.60	12.5	5.0	0.0
C	1	661	PIMA	1.10	8.3	6.0	0.0
C	1	660	PIMA	1.46	9.5	2.8	0.0
C	1	659	PIMA	1.00	9.0	3.1	0.0
C	1	658	PIMA	3.25	19.7	5.9	0.0
C	1	657	PIGL	3.90	25.7	11.5	0.0
C	2	656	PIGL	6.20	30.5	8.1	0.0
C	2	655	PIGL	2.50	13.2	7.1	0.0
C	2	654	PIMA	1.56	10.0	5.5	0.0
C	2	653	PIGL	2.65	12.7	6.5	0.0
C	2	652	PIMA	1.27	9.6	3.9	0.0
C	2	651	PIMA	2.40	11.7	4.5	0.0
C	2	650	PIMA	2.80	18.3	8.5	0.0
C	2	649	PIMA	2.89	18.6	6.8	0.0
C	2	648	PIMA	1.35	10.2	5.0	0.0
C	2	647	PIMA	1.45	10.1	3.2	0.0
C	2	646	PIMA	1.44	11.0	4.8	0.0

C	3	645	PIMA	1.63	11.5	8.2	0.0
C	3	644	PIMA	1.10	8.2	4.3	0.0
C	3	643	PIMA	1.47	11.5	3.9	0.0
C	3	642	PIGL	2.20	8.5	1.7	0.0
C	3	641	PIMA	1.55	12.5	3.5	0.0
C	3	640	PIMA	2.19	12.1	2.5	0.0
C	3	639	PIMA	1.22	9.5	2.2	0.0
C	4	638	PIMA	1.55	10.0	1.7	0.0
C	4	637	PIMA	1.72	12.0	3.7	0.0
C	4	636	PIMA	1.82	12.5	0.0	0.0
C	4	635	PIMA	1.85	12.6	2.1	0.0
C	4	634	PIMA	2.35	11.8	1.8	0.0
C	4	633	PIMA	1.92	11.9	3.0	0.0
C	4	632	PIMA	2.80	15.9	1.1	0.0
C	4	631	PIMA	3.52	20.7	6.0	0.0
C	4	630	PIMA	2.17	16.7	5.1	0.0
C	5	629	PIMA	1.90	12.1	5.5	0.0
C	5	628	PIMA	1.57	11.7	4.2	0.0
C	5	627	PIMA	1.56	12.5	6.5	0.0
C	5	626	PIMA	1.15	8.3	4.1	0.0
C	5	625	PIMA	2.95	15.3	5.9	0.0
C	5	624	PIMA	2.75	18.4	4.7	0.0
C	5	623	PIMA	2.33	15.4	6.3	0.0
C	5	622	PIMA	1.68	11.6	2.6	0.0
C	5	621	PIGL	3.27	16.6	3.8	0.8
C	5	620	PIMA	2.32	16.0	5.2	0.0

Treatment

Avg. DBH $\leq$ 2"	**Avg. DBH 2 - 4"**	**Avg. DBH 4 - 9"**	**Avg. DBH > 9"**	**Avg. DBH > 0"**
1.56	**2.56**	**4.92**	**0.00**	**2.52**
Avg. Ht. $\leq$ 2"	**Avg. Ht. 2 - 4"**	**Avg. Ht. 4 - 9"**	**Avg. Ht. > 9"**	**Avg. Ht. > 0"**
11.65	**16.70**	**27.47**	**0.00**	**16.34**
Avg. Ht. ladder fuel $\leq$ 2"	**Avg. Ht. ladder fuel 2 - 4"**	**Avg. Ht. ladder fuel 4 - 9"**	**Avg. Ht. ladder fuel > 9"**	**Avg. Ht. ladder fuel > 0"**
3.84	**4.03**	**4.47**	**0.00**	**4.02**

Avg. Ht. to live crown ≤ 2"	Avg. Ht. to live crown 2 - 4"	Avg. Ht. to live crown 4 - 9"	Avg. Ht. to live crown > 9"	Avg. Ht. to live crown > 0"
4.50	4.65	4.80	0.00	4.62

Avg. live crown length ≤ 2"	Avg. live crown length 2 - 4"	Avg. live crown length 4 - 9"	Avg. live crown length > 9"	Avg. live crown length > 0"
7.15	12.05	22.67	0.00	11.72

Control

Avg. DBH ≤ 2"	Avg. DBH 2 - 4"	Avg. DBH 4 - 9"	Avg. DBH > 9"	Avg. DBH > 0"
1.47	2.80	6.20	0.00	2.17

Avg. Ht. ≤ 2"	Avg. Ht. 2 - 4"	Avg. Ht. 4 - 9"	Avg. Ht. > 9"	Avg. Ht. > 0"
10.72	16.08	30.50	0.00	13.54

Avg. Ht. ladder fuel ≤ 2"	Avg. Ht. ladder fuel 2 - 4"	Avg. Ht. ladder fuel 4 - 9"	Avg. Ht. ladder fuel > 9"	Avg. Ht. ladder fuel > 0"
0.00	0.04	0.00	0.00	0.02

Avg. Ht. to live crown ≤ 2"	Avg. Ht. to live crown 2 - 4"	Avg. Ht. to live crown 4 - 9"	Avg. Ht. to live crown > 9"	Avg. Ht. to live crown > 0"
4.07	5.40	8.10	0.00	4.75

Avg. live crown length ≤ 2"	Avg. live crown length 2 - 4"	Avg. live crown length 4 - 9"	Avg. live crown length > 9"	Avg. live crown length > 0"
6.65	10.69	22.40	0.00	8.79

Appendix G

Control	≤ 2"	2 - 4"	4 - 9"	> 9"	> 0"
Most common species	*Picea mariana*	*Picea mariana*	*Picea mariana*		*Picea mariana*
Second most common species	*Betula papyrifera*	*Betula papyrifera*	*Betula papyrifera*		*Betula papyrifera*
Tree density (stems/ac)	4562	447	19	0	5028
Live	4135	447	19	0	4601
Dead	427	0	0	0	427
Avg. DBH					
Live (in)	1.47	2.80	6.20	0.00	2.17
Live (cm)	3.75	7.12	15.75	0.00	5.51
Dead					
Avg. height					
Live (ft)	10.72	16.08	30.50	0.00	13.54
Live (m)	3.27	4.90	9.30	0.00	4.13
Dead					
Avg. ladder fuel height					
Live (ft)	0.00	0.04	0.00	0.00	0.02
Live (m)	0.00	0.01	0.00	0.00	0.01
Dead					
Avg. height to live crown (ft)	1.64	1.64	1.64	0.00	1.64
Avg. height to live crown (m)	0.50	0.50	0.50	0.00	0.50
Avg. tree wt. (grams) ≤1/4"	543.01	2017.39	10246.99	0.00	726.32
Total diameter class tree wt.(tons/ac)	2.48	0.99	0.21	0.00	3.68
Total diameter class tree wt.(kg/ac)	2245.33	901.77	194.69	0.00	3341.80
Live crown mass ≤1/4" (kg/m^2)	0.55	0.22	0.05	0.00	0.83
Avg. live crown length (m)	2.76	4.40	8.80	0.00	3.25
Crown Bulk Density ≤1/4" (kg/m^3)	0.199	0.050	0.006	0.000	0.255

Treatment	≤ 2"	2 - 4"	4 - 9"	> 9"	> 0"
Most common species	*Picea mariana*	*Picea mariana*	*Picea mariana*		*Picea mariana*
Second most common species	*Betula papyrifera*	*Betula papyrifera*	*Betula papyrifera*		*Betula papyrifera*
Tree density (stems/ac)	184	272	39	0	495
Live	184	272	39	0	495
Dead	0	0	0	0	0
Avg. DBH					
Live (in)	1.56	2.56	4.92	0.00	2.52
Live (cm)	3.96	6.51	12.50	0.00	6.41
Dead					
Avg. height					
Live (ft)	11.65	16.70	27.47	0.00	16.34
Live (m)	3.55	5.09	8.37	0.00	4.98
Dead					
Avg. ladder fuel height					
Live (ft)	3.84	4.03	4.47	0.00	4.02
Live (m)	1.17	1.23	1.36	0.00	1.23
Dead					
Avg. height to live crown (ft)	4.50	4.65	4.80	0.00	4.62
Avg. height to live crown (m)	1.37	1.42	1.46	0.00	1.41
Avg. tree wt. (grams) ≤1/4"	607.08	1679.44	6384.66	0.00	1651.54
Total diameter class tree wt. (tons/ac)	0.12	0.50	0.27	0.00	0.90
Total diameter class tree wt. (kg/ac)	111.70	456.81	249.00	0.00	817.51
Live crown mass ≤1/4" (kg/m^2)	0.03	0.11	0.06	0.00	0.20
Avg. live crown length (m)	2.18	3.67	6.91	0.00	3.57
Crown Bulk Density ≤1/4" (kg/m^3)	0.013	0.031	0.009	0.000	0.052

Appendix H

Conversion factors

International units of measure	Multiply by	Obtain	Inverse
Centimeter (cm)	0.39370	Inches (in)	2.54
Degree Celsius (C)	5/9 (^oF - 32)	Degree Fahrenheit (F)	(9/5^{o}C) + 32
Grams per cubic centimeter (g/cm^3)	62.428	Pounds per cubic foot (lb/ft^3)	0.016018
Hectares (ha)	2.4711	Acres (ac)	0.40469
Kilograms per cubic meter (kg/m^3)	0.062428	Pounds per cubic foot (lb/ft^3)	16.018
Kilograms per square meter (kg/m^2)	0.20482	Pounds per square foot (lb/ft^2)	4.8824
Kilometers (km)	0.62137	Miles (mi)	1.6093
Kilometers per hour (km/hr)	0.62137	Miles per hour (mi/hr)	1.6093
Kilowatts per meter (kW/m)	0.28868	Btu feet per second (btu/ft/sec)	3.46404
Meters (m)	3.2808	Feet (ft)	0.3048
Meters (m)	0.049709	Chains (ch)	20.117
Meters per minute (m/min)	2.98255	Chains per hour (ch/hr)	0.33528
Meters per second (m/sec)	178.95312	Chains per hour (ch/hr)	0.00559